



Europäisches Patentamt  
European Patent Office  
Office européen des brevets

Publication number:

**0 129 753**  
**A1**

## EUROPEAN PATENT APPLICATION

Application number: 84106547.7

Int. Cl.<sup>4</sup>: G 01 N 9/00

Date of filing: 07.06.84

Priority: 21.06.83 US 506314

Date of publication of application:  
02.01.85 Bulletin 85/1

Designated Contracting States:  
AT BE CH DE FR GB IT LI NL SE

Applicant: QUARTZTRONICS, INC.  
1020 Atherton Drive Bldg. C, Suite 202  
Salt Lake City Utah 84107(US)

Inventor: Ward, Roger W.  
1345 Emerson Avenue  
Salt Lake City Utah 84105(US)

Representative: Patentanwälte Grünecker, Dr.  
Kinkeldey, Dr. Stockmair, Dr. Schumann, Jakob, Dr.  
Bezold, Meister, Hilgers, Dr. Meyer-Plath  
Maximilianstrasse 58  
D-8000 München 22(DE)

**54** Fluid density measurement apparatus and method.

**57** Fluid density measuring apparatus and method for directly measuring fluid density or indirectly measuring pressure, temperature, acceleration, flow velocity, differential pressure and other parameters affecting the apparatus. The apparatus includes a generally rigid hollow housing (4) having openings (8) (12) through which fluid may flow to the interior of the housing, and a vibratory single-ended tuning fork (24) mounted in the housing. The apparatus also includes circuitry (30) for causing the tines of the tuning fork to resonate, for example, 180 degrees out of phase in a transverse direction, with the frequency of the tines varying with variation in the density of the fluid surrounding the tines. Circuitry is also included for determining the frequency at which the tuning fork tines resonate. When the density of the fluid into which the housing is placed changes, the frequency of vibration of the tines of the tuning fork is caused to change to provide a measure of the density change.

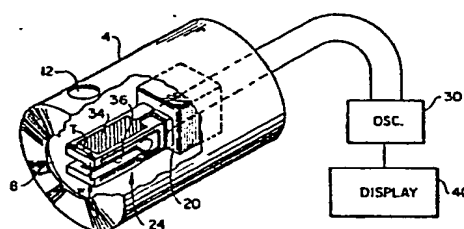


Fig. 1

EP 0 129 753 A1

1

5

10 FLUID DENSITY MEASUREMENT APPARATUS AND METHOD

This invention relates to a method and apparatus for measuring fluid density and for measuring parameters which may cause the density of the fluid to change.

15

It has been known for some time that a vibratory element, such as a quartz crystal, when exposed to a gas will change its frequency as the gas pressure changes. See, for example, M. A. Cotter, Patent No. 4,126,049, J. W. Stansfeld, Patent No. 4,232,544, P. N. Potter, Patent No. 4,178,804, "Vacuum Microbalance Techniques", Edited by Klaus H. Behrndt, 1966, Plenum Press, N.Y., and A. Genis and D. E. Newell, "Using The X-Y Flexure Watch Crystal as a Pressure-Force Transducer" delivered at the Thirty First Annual Frequency Control Symposium, Atlantic City, New Jersey, June, 1977. Although these references recognize that the frequency of a vibratory

20

25

1 element will change with a change in pressure of the  
gas surrounding the element, none recognized or disclosed  
that gas density measurement could be utilized as the  
mechanism for measuring pressure, and thus none recognized  
5 the full potential of gas density determination as a  
vehicle for measuring a variety of other parameters  
such as temperature, acceleration, flow, force, differential  
pressure, etc. One prior art reference, Theory of Vibrating  
Systems and Sound, by Irving B. Crandell, Von Nostrand,  
10 1926, pp. 124-133, disclosed that the frequency of a  
vibrating string or rod would change with a change in  
density of the medium in which the string was placed,  
but failed to recognize how this phenomenon could be  
employed in practice and, in fact, misleadingly stated  
15 that the change in frequency resulting from a change in  
density would not be great unless the density of the  
medium were comparable to that of the rod.

It has been discovered that a principal mechanism by  
20 which a flexure or torsional mode vibratory element  
exposed to a fluid (liquid or gas) is caused to change  
its frequency is not an intrinsic change in pressure  
but rather is a change in the density of the fluid.  
The effect is equivalent to that of adding mass to the  
25 vibratory element (increase in density) or taking mass  
from the vibratory element (decrease in density) to  
respectively reduce or increase the frequency of vibration.

1 Viewed another way, the effect may be likened to that  
of an object "flapping in the wind". It has been  
found that when the surface area of the object normal  
to the direction of movement or vibration of the object  
5 is increased, the "pushing" of the fluid by the object  
becomes more difficult resulting in a slowing of the  
vibration, and vice versa. Recognizing this mechanism  
allows for optimizing the sensitivity of vibratory  
devices used for measuring density directly or for  
10 measuring other parameters such as pressure, temperature,  
etc. In particular, the greater the surface area of  
the vibratory element, the greater will be the sensitivity  
of the frequency of vibration to fluid density changes.  
Also, by proper selection of the working fluid in which  
15 the vibratory element is placed, different measurement  
objectives can be achieved. For example, in a gas  
density device, use of a more dense gas such as argon  
will give rise to greater sensitivity, whereas use of a  
less dense gas, such as helium, will allow detection of  
20 density (and thus pressure or other parameter) changes  
over a wider range.

The above will become more apparent from a mathematical  
analysis of the effect fluid density has on a vibratory  
25 element. The pressure due to the frontal area of a  
rectangular bar having a thickness  $T$  and a width  $w$ ,  
which is vibrating in the  $w$  direction, moving ambient  
fluid is given by:

$$1 \quad P = -2\pi f r U_0 T C \sin(2\pi ft),$$

where  $f$  is the frequency of vibration,  $r$  is the density of the ambient fluid,  $U_0$  is the peak vibration velocity of the bar in the  $w$  direction, and  $C$  is a shape factor for edge effects and has a value near unity. The force  $F$  per unit length acting on the bar due to the pressure is  $2PT$ , since both sides of the bar are acting on the fluid. Therefore,

10

$$F = -4\pi f r U_0 T^2 C \sin(2\pi ft).$$

Since the velocity  $U$  of the vibrating bar is related to the displacement  $Y = Y_0 \sin(2\pi ft)$  by:

15

$$U = 2\pi f Y_0 \cos(2\pi ft),$$

then the force  $F$  per unit length is given by:

20

$$F = -8\pi^2 f^2 r Y_0 T^2 C \sin(2\pi ft).$$

The conventional equation for equilibrium of a laterally vibrating beam with the force  $F$ , from equation 4, added to the inertial forces is:

25

$$EI \frac{d^4 Y}{dx^4} + (r_q T_w + 2r T^2 C) 4\pi^2 f^2 Y = 0,$$

1 where  $E$ ,  $I$ , and  $r_q$  are Young's Modulus, moment of  
 inertia, and density of the vibrating beam respectively.  
 The resonant frequency  $f_0$ , for  $r=0$  (no ambient fluid),  
 is thus perturbed by the added term  $2rT^2C$  in equation  
 5 5. The added term is of the form of an added mass per  
 unit length, just as  $r_q Tw$  is the mass per unit length  
 of the bar. The resulting resonant frequency  $f$ , from  
 equation 5, is given by:

$$10 \quad (f/f_0)^2 = \frac{1}{1 + \frac{2rTC}{r_q w}}$$

For small perturbations,

$$15 \quad \frac{f}{f_0} = 1 - \frac{rTC}{r_q w},$$

$$\text{or } (f - f_0)/f_0 = rTC/r_q w.$$

20 From the last equation, it is apparent that the frequency  
 of a vibrating element is substantially linearly dependent  
 upon the density of the working fluid and that increased  
 sensitivity of a vibratory element can be achieved by  
 both increasing the thickness-to-width ratio of the  
 vibrating bar and selecting a more dense fluid as the  
 25 working medium.

1 It is an object of the invention to provide a highly  
sensitive apparatus and method for measuring directly  
density and changes in density of fluid to which the  
apparatus is exposed or other parameters such as pressure,  
5 temperature, etc.

It is another object of the invention to provide such  
apparatus and method in which measurement over large  
scale ranges can be achieved or high resolution can be  
10 obtained.

It is a further object of the invention to provide such  
apparatus and method which is simple in construction,  
rugged, and inexpensive.

15

It is an additional object of the invention to provide  
such apparatus and method in which sensitivity can be  
controlled by appropriate selection of the dimensions  
of the vibratory element.

20

The above and other objects of the invention are realized  
in a specific illustrative embodiment of a fluid density  
measurement device which includes a generally rigid  
hollow housing, and an elongate bar mounted in the  
25 housing and adapted to vibrate in the flexure mode,  
where the bar has a thickness  $T$  to width  $w$  ratio of  $T/w \geq$   
 $0.1$ , or in the torsional mode, where the bar has a

1 generally rectangular cross-section. The housing  
includes openings through which fluid may enter to  
contact the bar. Circuitry is provided for causing the  
bar to resonate, with the frequency of resonation  
5 varying with variation in the density of the fluid  
surrounding the bar. To measure the density of a  
fluid, the device is simply placed in the fluid so that  
the fluid enters the housing and surrounds the bar.  
The resulting change in the resonant frequency of  
10 vibration of the bar is proportional to the change in  
density of the fluid.

The device can be adapted to measure a variety of other  
parameters such as pressure, differential pressure,  
15 temperature, acceleration, force, flow velocity, etc.  
For example, by sealing a movable wall over the openings  
of the housing so that as the wall moves, the volume in  
the housing varies, and placing a gas in the housing,  
pressures exterior to the housing can be measured.  
20 That is, as the exterior pressure varies, the wall is  
caused to move to vary the volume in the housing and  
thus the density of the gas and this, in turn, causes  
the frequency of vibration of the bar to vary. Appropriate  
selection of the gas contained in the housing can  
25 provide either a substantially full scale range measurement  
for the pressures but with less resolution, or a smaller  
scale range measurement with greater resolution. For



1    exampl , use of a more dense gas will yield greater  
resolution, whereas use of a less dense gas will provide  
a more full scale range measurement.

5    In accordance with one aspect of the invention, a  
single ended tuning fork configuration is employed as  
the vibratable element. The desired thickness-to-width  
ratio of the tines of the tuning fork may be readily  
provided with the single ended tuning fork configuration.

10

In the drawings:

The above and other objects, features and advantages of  
the invention will become apparent from a consideration  
15 of the following detailed description presented in  
connection with the accompanying drawings in which:

FIG. 1 is a perspective, partially cut away view of a  
fluid density measuring device made in accordance with  
20 the principles of the present invention;

FIG. 2 is a side, elevational, partially cut-away view  
of a gas density/pressure transducer utilizing a bellows  
as the pressure transmitting element;

25

FIG. 3 shows a side, cross-sectional view of a gas  
density/pressure transducer utilizing a diaphragm as  
the pressure transmitting element;

1 FIG. 4 is a side, cross-sectional view of a gas density/temperature transducer made in accordance with the principles of the present invention;

5 FIG. 5 is a side, elevational, partially cut-away view of a gas density/acceleration transducer;

FIG. 6 is a side, elevational, partially cut-away view of a gas density/force transducer;

10

FIG. 7 is a side, elevational, partially cut-away view of a gas density/flow velocity transducer; and

FIG. 8 is a side, elevational, partially cut-away view  
15 of a gas density/differential pressure transducer.

Referring now to the drawings:

FIG. 1 shows one embodiment of a fluid density measurement  
20 device which takes advantage of the fluid density/frequency of vibration phenomenon. The device includes a generally hollow cylindrical (but other shapes could also be utilized) housing 4. The housing has an opening 8 at one end and another opening 12 on the side to allow  
25 fluid to which the housing is exposed to flow into the housing. The housing 4 may be made of any material sufficiently rigid to provide protection for the apparatus

- 1 which will be mounted in the housing. Openings in the housing may be provided at any locations sufficient to allow fluid to enter the housing.
- 5 Disposed in the housing 4 and mounted thereto by way of a mounting base 20 is a single ended vibratable tuning fork 24 having a pair of tines joined together at one end and maintained in a generally spaced-apart, parallel arrangement. The thickness of the tines is given by T
- 10 and the width is given by w as indicated in FIG. 1. The tuning fork 24 may be made integral with the mounting block 20, or it may be made separate and then mounted on the mounting block 20 which, in turn, is mounted to the inside, bottom wall of the housing 4. This could
- 15 be done by a suitable adhesive or other fastening devices. Advantageously, the tuning fork 24 is made of quartz, and the mounting base 20 is a nonconducting material such as glass.
- 20 An oscillator circuit 30 is coupled to thin electrode films or coatings 34 and 36 disposed on various surfaces of the tuning fork 24 in a conventional way, as shown in the drawing. Application of A.C. signals by the oscillator 30 to the electrode films 34 and 36 produces
- 25 stress forces in the tines to cause the tines to vibrate in a transverse direction (flexure mode) in  $180^\circ$  phase opposition. That is, the tines are caused to move in

1 the w direction outwardly away from each other and then  
inwardly toward each other, etc., in a well known  
manner and at a characteristic or desired natural  
resonant frequency. When the density of fluid to which  
5 the housing 4 is exposed changes, the frequency of  
vibration of the tines is caused to change, and the  
magnitude of the change serves as a measure of the  
change in density. The oscillator 30 follows in frequency  
the frequency of the tuning fork 24 and so the change  
10 in frequency of the tuning fork can be measured by  
simply measuring the output frequency of the oscillator.  
A conventional counter and display 40 may be connected  
to the oscillator 30 to provide a readout of the densities  
being measured.

15 Resolution can be improved by increasing the thickness-  
to-width ratio  $T/w$  of the tuning fork tines. However,  
fabrication problems limit, to a certain extent, the  
thickness-to-width ratio which may be obtained for  
20 quartz crystal tuning forks made by photolithographic  
processes. It has been found that a thickness-to-width  
ratio  $T/w$  of 0.1 or greater is suitable. Crystals  
thicker than about 0.25 mm cannot be etched through  
readily; tines narrower than about 0.12 mm are too  
25 narrow to allow proper electrode definition. This  
limits  $T/w$  to about two for photolithographically  
produced quartz crystal tuning forks. For wire-sawed  
forks, a thickness of 1 mm and width of 0.12 are practical  
limits for a  $T/w$  ratio of eight.

1 Although the electrode coatings 34 and 36 of FIG. 1 are  
arranged to cause the tuning fork 24 to vibrate in the  
flexure mode, they could be arranged to cause the  
tuning fork to vibrate in what is called the torsional  
5 mode. See R. Dinger, 37th Frequency Control Symposium,  
Philadelphia, 1982. A change in density of fluid  
surrounding the tuning fork 24 would also cause a  
proportional change in frequency of vibration of the  
tuning fork resonating in the torsional mode, provided  
10 the tuning fork tines were not cylindrical in shape.  
In particular, the tuning fork tines should have rectangular  
cross-sections for torsional mode operation so that as  
the tines vibrate, they will push against the fluid in  
which they are placed.

15 There are a variety of uses of the device of FIG. 1  
including measurement of the extent to which a cavity  
has been evacuated of gas, measurement of the degree of  
contamination of a fluid with other fluids or materials  
20 (which would cause a change in density), measurement of  
the density of the air/fuel mixture used in internal  
combustion engines to assist in maximizing power output  
and reducing polluting emissions, etc.

25 FIG. 2 shows an embodiment of a gas density/pressure  
transducer made in accordance with the present invention.  
The transducer apparatus includes a generally rigid

1 hollow housing 42, open at one end 42a. Sealingly  
placed over the opening is a bellows 44 having an  
accordian-like sidewall 44a and a generally flat endwall  
44b. The housing 42 may be made of any rigid material  
5 capable of withstanding the fluid pressure to which it  
would be subjected and, advantageously, capable of  
withstanding corrosion. For example, stainless steel  
might be used. The bellows 44 would advantageously be  
made of a fairly flexible material, at least for the  
10 side walls 44a, such as electroless nickel. It is  
desired that the bellows 44 be fairly soft and flexible  
so that any pressure to which the housing 42 and bellows  
44 are subjected will be transmitted to the interior of  
the housing.

15 Contained in the housing 42 is a working gas, preferably  
one of the inert gases such as argon, radon, helium,  
etc. It is the change in density of this gas which  
will be measured to provide a measure of the exterior  
20 pressure.

A single-ended tuning fork 46 is disposed in the housing  
42, and is caused to vibrate in either the flexure or  
torsional modes by an oscillator circuit 47 which is  
25 coupled to a display 48.

1 If a wide measuring range for the pressures is desired,  
then a less dense gas such as helium, neon, hydrogen,  
methan , etc., may be used as the working fluid in the  
housing 42. Preferably, inert gases would be used to  
5 avoid problems of corrosion of the housing 42 or of the  
vibratory element and its electrodes or other driving  
mechanism, and of potential combustion problems. If a  
less dense gas is used, a greater exterior pressure  
change is needed to produce a given change in the  
10 frequency of vibration of the tuning fork 46. Thus, a  
wide range of pressures may be measured for whatever  
range of frequency changes is possible with the apparatus.  
For example, pressures of helium from 0.07 to 700 MPa  
(Megapascal can be measured with a sensitivity of 36  
15 parts per million per MPa for a tuning fork having  $T/w \geq$   
0.75.

If greater sensitivity or resolution is desired, then a  
more dense gas such as argon, xenon, radon, krypton,  
20 etc., may be used as the working fluid in the housing  
42. Because such gases are more dense, any change of  
pressure will cause a more significant change in frequency  
of vibration of the tuning fork 24 per equation (7),  
and so even small pressure changes will be detectable.  
25 For example, using argon gas, the same tuning fork  
above has a sensitivity of 360 ppm/MPa over a pressure  
range of 0.07 to 70 MPa.

1 As indicated earlier, resolution, whether using a more  
dense or less dense gas as the working fluid, can be  
improved by increasing the thickness-to-width ratio  $T/w$   
of the tuning fork tines. It has been found that a  
5 thickness-to-width ratio  $T/w$  of 0.5 or greater is  
suitable regardless of the type of working gas employed.  
For a higher density gas which results in greater  
sensitivity, the thickness-to-width ratio may be as low  
as about 0.1 and still provide suitable results.

10

FIG. 3 shows an alternative embodiment of a fluid  
density/pressure transducer. This embodiment includes  
a housing 50, an upper portion or chamber 54 of which  
is generally hemispherical having an opening 56 and a  
15 lower portion or chamber 58 of which is generally  
cylindrical and smaller in diameter than the hemispherical  
portion 54. Mounted over the opening 56 is a diaphragm  
60 made, for example, of Viton (trademark). A tuning  
fork 64 is mounted in the lower portion 58 of the  
20 housing 50 out of the way of the hemispherical portion  
54. An oscillator circuit 68 is coupled to the tuning  
fork to cause the tuning fork to vibrate, and a display  
72 is provided to give a visual indication of the  
frequency and pressure being measured.

25



- 1 The diaphragm 60 is sealingly mounted over the opening  
56 of the housing 50 to prevent introduction of ambient  
fluid into the housing. The housing 50 includes a  
working gas as discussed for the apparatus of FIG. 2.
- 5 As the exterior pressure changes, the diaphragm 60 is  
caused to move inwardly in the housing (with pressure  
increase) or outwardly from the housing (with a pressure  
decrease) to thus cause a change in density of the gas  
contained in the housing. The frequency of vibration  
10 of the tuning fork 64, of course, tracks the change in  
the gas density to provide the desired measurement.

The portion 54 of the housing 50 is formed with hemispherical  
walls so that they will act to prevent movement of the  
15 diaphragm into contact with the tuning fork 64 and will  
allow compression of most of the gas in the housing 50  
into chamber 58. Obviously, contact of the tuning fork  
64 by the diaphragm 60 would interfere with the operation  
of the apparatus and the measurement being taken. A  
20 screen 76 could also be provided at the junction of the  
hemispherical portion 54 and the lower portion 58 to  
further block any movement of the diaphragm towards the  
tuning fork 64.

- 25 The FIG. 3 embodiment can achieve greater pressure  
measurement ranges than the FIG. 2 embodiment because  
higher compression ratios can be obtained with the FIG.

1 3 embodiment than with the FIG. 2 embodiment. Stated  
another way, there is too much dead space which cannot  
be compressed with a bellows arrangement, unlike a  
diaphragm arrangement wherein most of the interior  
5 space can be compressed. That is, as the exterior  
pressure increases, the diaphragm is able to move into  
the chamber 54 to contact and conform to the hemispherical  
walls of the chamber and thereby take up most of the  
space within the housing 50.

10  
FIG. 4 shows a gas density/temperature transducer of a  
structure known as a "filled thermal system". This  
structure is comprised of a first generally rigid  
hollow housing 80, a second generally rigid hollow  
15 housing 84, and a capillary tube 88, having an internal  
volume substantially less than the volume of housing  
80, interconnecting the two housings. A tuning fork 86  
is mounted in the housing 84, and is coupled to an  
oscillator circuit 88 which, in turn, is coupled to a  
20 display 90. Advantageously, the housings 80 and 84 and  
the capillary 88 is made of a material possessing high  
strength at high temperatures, such as stainless steel  
or Inconel (trademark). Also, noble gases are a preferred  
fluid for placement in the housings 80 and 84 and the  
25 capillary tube 88.

1 To measure temperature changes, the housing 88 is  
expos d to the medium whose temperature is to be measured  
so that the fluid contained in the housing will increase  
in temperature and expand, or decrease in temperature  
5 and contract, depending upon the temperature of the  
medium. With such expansion or contraction, the fluid  
molecules are either driven from housing 80 toward  
housing 84 or vice versa. Thus, the gas density in  
housing 84 is caused to change with a change in temperature  
10 of the gas in housing 80. Because of the remoteness  
of housing 84 from housing 80 and the insulative nature  
and size of the capillary tube 88, the temperature of  
the gas in housing 84 does not appreciably change with  
the change in temperature of the gas in housing 80.  
15 With a change in gas density in housing 84, the frequency  
of vibration of the tuning fork 86 changes to provide a  
measure of the temperature change.

In the event that temperature contamination of the  
20 fluid in housing 84 occurs to the extent of introducing  
significant error, a temperature sensor could be placed  
in the housing 84 to track temperature changes there  
and then the temperature determination made by the  
oscillator 88 could be corrected to account for the  
25 unwanted temperature changes in the housing 84. This  
could be done by using conventional microprocessor or  
circuit correction techniques. And, of course, such

1 temperature compensation might be desirable for all the  
fluid density transducer embodiments described herein.

The selection of argon or other noble gases below argon  
5 on the periodic chart for use as the working fluid in  
housing 80 is made because such gases have critical  
temperatures below  $-100^{\circ}\text{C}$  and so will not condense at  
any pressure above that temperature. Thus such gases  
behave as nearly ideal gases for all pressures and  
10 temperatures normally encountered where temperature or  
pressure measurements are desired.

The FIG. 5 apparatus is a gas density/acceleration  
transducer constructed similar to the transducer of  
15 FIG. 2, but further including a piece of material 100  
of known mass mounted on the flat wall 104 of a bellows  
108. As the FIG. 5 apparatus is accelerated (or decelerated)  
in the direction indicated by the arrow, the mass 100  
tends to compress (or expand) the bellows 108 and thus  
20 the gas contained in housing 112. The resulting change  
in density is detected by a tuning fork 116 and oscillator  
120. The change in frequency of vibration of the  
tuning fork 116 is proportional to the change in acceleration  
of the apparatus and so can provide a measure of such  
25 acceleration.

1 The FIG. 6 apparatus is for a gas density/force transducer,  
again constructed similar to the apparatus of FIG. 2.  
However, a generally flat receiving plate 130 is mounted  
on the flat wall 134 of a bellows 138. The apparatus  
5 of FIG. 6 is positioned so that the receiving plate 130  
is generally horizontal (but it could be used in other  
orientations). Forces, such as the weight of an object,  
are applied to the receiving plate 130 which causes the  
bellows 138 to compress (or expand) and this, in turn,  
10 increases (or decreases) the density of gas in housing  
142 surrounding a tuning fork 146. The frequency of  
vibration of the tuning fork 146 is thus caused to  
change and this change is proportional to the force  
applied to the bellows 138 which is to be measured.

15  
FIG. 7 shows apparatus for measuring the velocity of a  
medium flowing in a conduit 160. The apparatus is  
essentially the same as that of FIG. 2 and includes a  
housing 164, and a bellows 168 having a generally flat  
20 end wall 172. The apparatus is positioned in the  
conduit 160 by a brace 176 so that the end wall 172 of  
the bellows 168 faces "upstream". Higher velocities of  
the medium will cause a greater compression of the  
bellows 168 and thus a change in the density of the  
25 working gas in the housing 164. This will be detected  
by a change in the frequency of vibration of tuning  
fork 180 to provide a readout of the flow velocity of

1 the medium. Correction for pressure changes in the  
conduit 160 must be made, as the apparatus will also be  
influenced by said pressure changes.

5 The FIG. 8 apparatus is for measuring differential  
pressure, for example, in a medium flowing in a conduit  
200 through an orifice 204. Of course, the apparatus  
of FIG. 8 could be used for measuring the pressure  
differential in a variety of situations. The apparatus  
10 includes a bellows 208, housing 212, and tuning fork  
216 in the configuration described earlier. The bellows  
208 is coupled by way of a pivot or hinge coupling 220  
to a pivot rod 224. The pivot rod 224 extends laterally  
of a rocker beam 228 which is mounted to rock or pivot  
15 about a fixed pivot hinge 232. Bellows 236 and 240 are  
mounted at respective ends of the beam 228, and each is  
coupled by respective tubes 244 and 248 to communicate  
with different parts of the conduit 200. The pressures  
of the medium flowing in the different parts of the  
20 conduit are different, and it is this difference which  
is to be measured.

Because the medium is flowing in the conduit 200 in the  
direction indicated by the arrows, the pressure in tube  
25 244 would be higher than that in tube 248, and this  
pressure would operate through the bellows 236 against  
the left end of the beam, forcing it upwardly. The

1 bellows 236 and 240 are provided to allow movement of  
the beam 228 with respect to the tubes 244 and 248. As  
the left end of the beam 228 moves upwardly, the pivot  
rod 224 is caused to move away from the housing 212,  
5 expanding the bellows 208 and thus the gas contained  
therein. The resulting decrease in density of the gas  
is detected by the tuning fork 216 and an oscillator  
252. The magnitude of the change in gas density is  
proportional to the pressure differential between tubes  
10 244 and 248.

Of course, if the medium flowing in the conduit 200  
flows in the opposite direction of that indicated in  
the drawing, then the pressure in tube 248 would be  
15 higher than the pressure in tube 244 and so the pivot  
rod 224 would be caused to move toward the housing 212  
to thus increase the density of the gas in the housing.  
This increase would be detected to again provide measure  
of the differential pressure in the conduit 200.

20

A particular structure for utilizing the gas density  
transducer of the present invention is shown in FIG. 8,  
but it should be understood that a variety of other  
structures could also be employed.

25

- 1 In the manner described, a variety of fluid density  
transducers can be provided for measuring parameters  
such as pressure, temperature, acceleration, force or  
weight and differential pressure. All such transducers  
5 make use of the phenomenon that a change in fluid  
density surrounding a vibratory element causes a change  
in frequency of vibration of the element. By appropriate  
selection of the dimensions of the vibratory element  
and of the working fluids, either high resolution or  
10 full range measurement can be obtained and, in some  
instances, both can be achieved. The apparatus is  
relatively low in cost and yet is extremely rugged and  
reliable.
- 15 It is to be understood that the above-described arrangements  
are only illustrative of the principles of the present  
invention. Numerous modifications and alternative  
arrangements may be devised by those skilled in the art  
without departing from the spirit and scope of the  
20 present invention and the appended claims are intended  
to cover such modifications and arrangements. For  
example, although single-ended tuning forks were shown  
for each of the embodiments, single elongate bars,  
double-ended tuning forks, or other vibratable elements  
25 could also be used.



1

5

10

## C L A I M S

1. Fluid density measuring apparatus comprising  
a vibratory element,  
means for causing the element to resonate at a  
15 frequency  $f$ , said frequency varying with variation in  
density of fluid surrounding the element,  
means for determining frequency  $f$ , and  
a generally hollow housing in which the vibratory  
element is disposed, said housing being dimensioned to  
20 substantially surround the element and including at  
least one opening to allow fluid to enter into the  
housing.
2. Apparatus as in Claim 1 wherein the resonation  
25 causing means is adapted to cause the vibratory element  
to resonate in the flexure mode.

1 3. Apparatus as in Claim 1 wherein said vibrating  
element is an elongate bar having a generally rectangular  
cross-section, and wherein the resonation causing means  
is adapted to cause the vibratory element to resonate  
5 in the torsional mode.

4. Apparatus as in Claim 1 wherein said vibratory  
element is an elongate bar having a generally rectangular  
cross-section of thickness  $\underline{T}$  and width  $\underline{w}$ , where  $T/w \geq$   
10 0.1.

5. Apparatus as in Claim 4 wherein the resonation  
causing means is adapted to cause the vibratory element  
to resonate in the flexure mode in the  $\underline{w}$  direction.  
15

6. Gas density/pressure transducer apparatus comprising  
a generally rigid hollow housing having an opening  
on one side,  
a movable wall disposed over said opening to vary  
20 the volume in the housing as the wall is moved,  
a gas contained in the housing,  
an elongate bar mounted in the housing and adapted  
to vibrate, said bar having a thickness  $\underline{T}$  and width  $\underline{w}$ ,  
where  $T/w \geq 0.1$ ,  
25 means for causing the bar to resonate at a frequency  
 $f$ , said frequency varying with variation in the density  
of the gas in the housing and thus the pressure, and  
means for determining the frequency  $f$ .

-3-

1 7. Apparatus as in Claim 6 wherein said movable wall  
comprises a diaphragm positioned over the opening to  
move into the housing or out of the housing, depending  
on exterior pressure.

5  
8. Apparatus as in Claim 7 wherein said housing is  
formed with a first chamber into which the diaphragm  
may move to reduce the volume of the housing, and a  
second chamber in communication with the first chamber  
10 and in which the elongate bar is disposed, said second  
chamber being equal to or smaller in volume than said  
first chamber.

15 9. Apparatus as in Claim 6 wherein said movable wall  
comprises a bellows.

20 10. Apparatus as in Claim 6 wherein said fluid is a  
gas selected from the group consisting of argon, xenon,  
radon, krypton, and freon.

25 11. Apparatus as in Claim 6 wherein said fluid is a  
gas selected from the group consisting of helium, neon,  
hydrogen, methane, and carbon monoxide.

1 12. Apparatus as in Claim 6 wherein said bar comprises  
a tuning fork having a pair of tines joined together at  
one end so that the tines are maintained in a spaced-  
apart generally parallel relationship, each tine having  
5 a thickness T and a width w, where  $T/w \geq 0.1$ .

13. Apparatus as in Claim 12 wherein said resonance  
causing means includes means for causing the tines of  
the tuning fork to resonate  $180^\circ$  out of phase in a  
10 transverse direction.

14. Gas density/pressure transducer apparatus comprising  
a generally rigid hollow housing having an opening  
on one side,  
15 a movable wall disposed over said opening to vary  
the volume in the housing as the wall is moved,  
a gas contained in the housing,  
an elongate bar mounted in the housing and adapted  
to vibrate, said bar having a generally rectangular  
20 cross-section,  
means for causing the bar to resonate at a frequency  
f in the torsional mode, said frequency varying with  
variation in the density of the gas in the housing and  
thus the pressure, and  
25 means for determining the frequency f.

1 15. Gas density/temperature transducer apparatus  
comprising

a first generally rigid hollow housing,

a gas contained in the first housing,

5 a second generally rigid hollow housing,

a vibratory element mounted in the second housing,

an elongate tube coupling the first housing to the  
second housing to enable communication therebetween,

10 wherein the volume of the tube is less than that of the  
first housing,

means for causing the element to resonate at a  
frequency  $f$ , said frequency varying with variation in  
the density of gas in the second housing and thus the  
temperature of gas in the first housing, and

15 means for determining the frequency  $f$ .

16. Apparatus as in Claim 15 wherein the gas is  
selected from the group of noble gases consisting of  
argon, xenon, radon, krypton, neon and helium.

20

17. Apparatus as in Claim 15 wherein said vibratory  
element comprises a tuning fork having a pair of spaced-  
apart, generally parallel tines joined together at one  
end, each tine having a thickness  $\underline{T}$  and a width  $\underline{w}$ ,  
25 where  $T/w \geq 0.1$ .

1 18. Apparatus as in Claim 17 wherein said resonation  
causing means includes means for causing the tines of  
the tuning fork to resonate  $180^{\circ}$  out of phase in a  
transverse direction.

5

19. Apparatus as in Claim 15 wherein said vibratory  
element is a bar having a generally rectangular cross-  
section, and said resonation causing means includes  
means for causing the bar to resonate in the torsional  
10 mode.

20. Gas density/acceleration transducer apparatus  
comprising

a generally rigid hollow housing having an opening  
15 on one side,

a movable wall disposed over said opening to vary  
the volume in the housing as the wall is moved,

a material of known mass attached to the movable  
wall to compress or expand the wall and the volume in  
20 the housing as the apparatus is accelerated or decelerated  
in a certain direction,

a gas contained in the housing,

a vibratory element disposed in the housing,

means for causing the element to resonate at a  
25 frequency  $f$ , said frequency varying with variation in  
the density of the gas in the housing and thus in  
acceleration or deceleration of the apparatus in said

1 certain direction, and

means for determining the frequency  $f$ .

21. Gas density/force transducer apparatus comprising  
5 a generally rigid hollow housing having an opening  
on one side,

a movable wall disposed over said opening to vary  
the volume in the housing as the wall is moved,

a gas contained in the housing,

10 means for applying a force to the movable wall,

a vibratory element disposed in the housing,

means for causing the element to resonate at a  
frequency  $f$ , said frequency varying with variation in  
the density of the gas in the housing and thus in the  
15 force applied to the movable wall, and

means for determining the frequency  $f$ .

22. Gas density/flow velocity transducer apparatus for  
measuring the flow velocity of a fluid, said apparatus  
20 comprising

a generally rigid hollow housing having an opening  
on one side,

a movable wall disposed over said opening to vary  
the volume in the housing as the wall is moved,

25 a gas contained in the housing,

a vibratory element disposed in the housing,

1 means for positioning the housing and movable wall  
in the stream of flow of the fluid whose velocity is to  
be measured so that the flow direction of the fluid is  
generally normal against the movable wall,

5 means for causing the element to resonate at a  
frequency  $f$ , said frequency varying with variation in  
the density of the gas in the housing and thus in the  
flow velocity of the fluid, and

means for determining the frequency  $f$ .

10

23. Gas density/differential pressure transducer  
apparatus for measuring the pressure differential  
between two pressure sources, said apparatus comprising  
a generally rigid hollow housing having an opening

15 on one side,

a movable wall disposed over said opening to vary  
the volume in the housing as the wall is moved,

a gas contained in the housing,

a vibratory element disposed in the housing,

20 a movable member coupled to the movable wall and

responsive to the pressure sources for moving in a  
first direction if the pressure from one source is  
greater than the pressure from the other to thereby  
compress the movable wall and volume in the housing,

25 and in a second direction if the pressure from the  
other source is greater than the pressure from the one  
source to thereby expand the wall and volume in the



-9-

1 housing, the extent of movement of the member being  
proportional to the pressure differential between the  
sources,

means for causing the vibratory element to resonate  
at a frequency  $f$ , said frequency varying with variation  
in the density of the gas in the housing and thus in the  
pressure differential between the sources, and

means for determining the frequency  $f$ .

10 24. Apparatus as in Claim 23 wherein said movable member  
comprises

a rocker arm mounted to pivot about an axis at or  
near the midpoint of the arm,

15 bellows mounted at each end of the rocker arm to  
enable communication between the ends of the arm and a  
respective pressure source so that each pressure source  
operates through a respective bellows to apply a force to  
a respective end of the arm,

20 a pivot arm attached to the rocker arm at about the  
midpoint thereof to extend laterally therefrom in the plane  
in which the rocker arm moves, and

pivot coupling means joining the pivot arm to the  
movable wall.

25 25. Gas density/pressure transducer comprising

a generally rigid hollow housing formed with first  
and second chambers which are in communication with one

1 another, and an opening formed on one side of the  
housing to communicate with the first chamber, said  
second chamber being smaller in volume than said first  
chamber,

5 a diaphragm disposed over said opening to move  
into and out of the first chamber to vary the volume in  
the housing as the external pressure varies,

a gas contained in the housing,

a vibratory element mounted in the second chamber,

10 means for causing the element to resonate at a  
frequency  $f$ , said frequency varying with variation in  
the density of the gas in the housing and thus in  
pressure, and

means for determining the frequency  $f$ .

15

26. A transducer as in Claim 25 wherein the interior  
walls of the first chamber are formed to be generally  
hemispherical, with the diaphragm positioned at the  
planar end of the chamber to move into the chamber and  
20 contact and conform to the walls of the first chamber  
as the exterior pressure increases, and wherein the  
second chamber is located generally opposite the planar  
end of the first chamber.

25

27. A transducer as in Claim 26 wherein the volume  
of the second chamber is less than the volume of the  
first chamber.

1 28. A gas density/pressure transducer comprising  
a generally rigid hollow housing having an opening  
on one side,

a movable wall disposed over said opening to vary  
5 the volume in the housing as the wall is moved,

a gas contained in the housing, said gas being  
selected from the group consisting of argon, xenon,  
radon, krypton and freon,

a vibratory element mounted in the housing,  
10 means for causing the element to resonate at a  
frequency  $f$ , said frequency varying with variation in  
the density of the gas in the housing and thus pressure,  
and

means for determining the frequency  $f$ .

15

29. A gas density/pressure transducer comprising  
a generally rigid hollow housing having an opening  
on one side,

a movable wall disposed over said opening to vary  
20 the volume in the housing as the wall is moved,

a gas contained in the housing, said gas being  
selected from the group consisting of helium, neon,  
hydrogen, methane and carbon monoxide,

a vibratory element mounted in the housing,  
25 means for causing the element to resonate at a  
frequency  $f$ , said frequency varying with variation in  
the density of the gas in the housing and thus pressure,  
and

1 means for determining the frequency  $f$ .

30. A method of measuring fluid density comprising

(a) providing a generally hollow housing having  
5 at least one opening through which fluid may flow to  
the interior of the housing,

(b) providing a vibratory element in the housing,

(c) causing the element to resonate at a frequency  
10  $f$ , said frequency varying with variation in the density  
of the fluid surrounding the element,

(d) placing the housing in fluid whose density is  
to be measured, and

(e) determining the frequency of vibration of the  
element.

15

31. A method as in Claim 30 wherein step (b) further  
comprises providing an elongate vibratory element  
having a generally rectangular cross-section of thickness  
 $T$  and width  $w$ , where  $T/w \geq 0.1$ , and wherein step (c)  
20 comprises causing the element to vibrate in the flexure  
mode in the  $w$  direction.

32. A method as in Claim 30 wherein step (b) further  
comprises providing an elongate vibratory element  
25 having a generally rectangular cross-section, and  
wherein step (c) comprises causing the element to  
vibrate in the torsional mode.

-13-

1 33. A method of measuring force related parameters comprising

(a) providing a generally rigid hollow housing having an opening on one side,

5 (b) providing a movable wall over the opening to vary the volume of the housing as the wall is moved,

(c) providing an elongate bar mounted in the housing, said bar having a generally rectangular cross-section,

10 (d) providing a gas in the housing to surround the bar,

(e) causing the bar to resonate at a frequency  $f$ , said frequency varying with variation in the density of the fluid surrounding the bar,

15 (f) placing the housing in a position so that the force to be measured acts on the wall to cause it to move, and

(g) determining the frequency of vibration of the bar.

20

34. A method as in Claim 33 wherein step (d) comprises providing a gas selected from the group consisting of argon, xenon, radon, krypton and freon.

25 35. A method as in Claim 33 wherein step (d) comprises providing a gas selected from the group consisting of helium, neon, hydrogen, methane and carbon monoxide.

-14-

1 36. A method as in Claim 33 wherein the force related  
parameter to be measured is pressure, and wherein step  
(f) comprises placing the housing in the medium whose  
pressure is to be measured.

5

37. A method as in Claim 33 wherein the force related  
parameter to be measured is acceleration, said method  
further including the step of providing a material of  
known mass attached to the movable wall, and wherein  
10 step (f) comprises positioning the housing in a body to  
be accelerated so that as the body is accelerated, the  
material causes the wall to compress or expand the  
volume in the housing.

15 38. A method as in Claim 33 wherein the force related  
parameter to be measured is the weight of an object,  
and wherein step (f) comprises placing the object on  
the movable wall to cause the wall to either compress  
or expand the volume in the housing.

20

39. A method as in Claim 33 wherein the force related  
parameter to be measured is flow velocity of a medium,  
and wherein step (f) comprises placing the housing in  
the stream of flow of the medium so that the movable  
25 wall faces generally in a direction opposite the direction  
of flow of the medium.

-15-

1 40. A method as in Claim 33 wherein the force related  
parameter to be measured is differential pressure  
between two pressure sources, said method further  
including the step of providing a movable member which  
5 moves in a first direction if the pressure from one  
source is greater than the pressure from the other, and  
in a second direction if the pressure from the other  
source is greater than the pressure from the one source,  
with the amount of movement of the member being proportional  
10 to the pressure differential between the sources, and  
wherein step (f) comprises coupling the movable member  
to the movable wall so that as the movable member moves  
in the first direction, the movable wall and volume in  
the housing are compressed, and as the movable member  
15 moves in the second direction, the movable wall and  
volume in the housing are expanded.

20

25

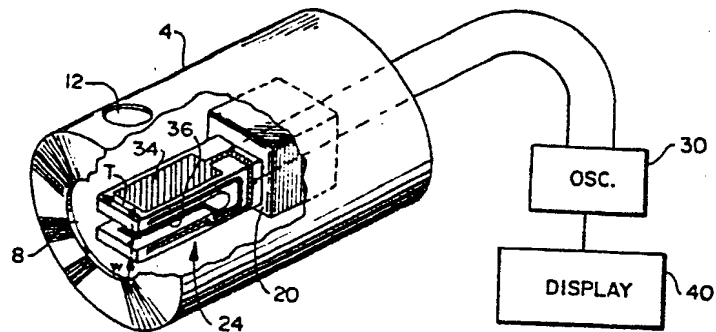


Fig. 1

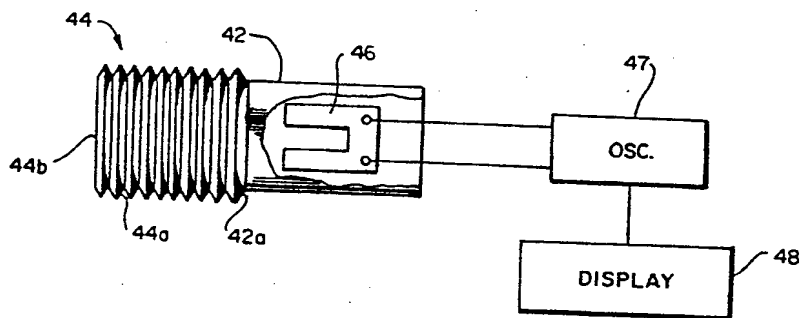


Fig. 2

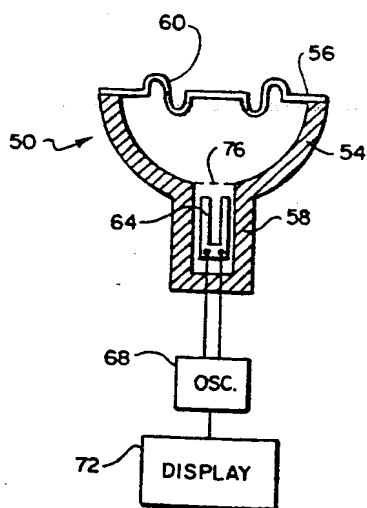


Fig. 3

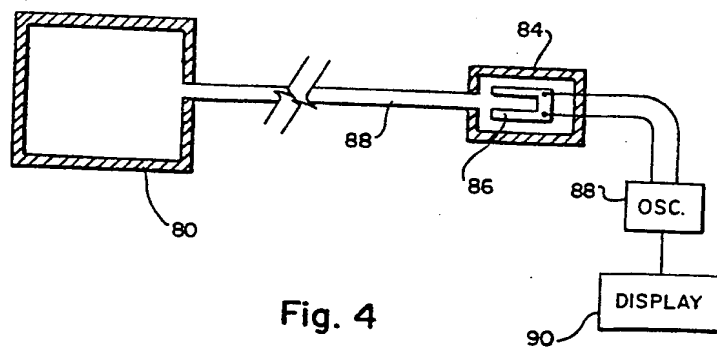


Fig. 4



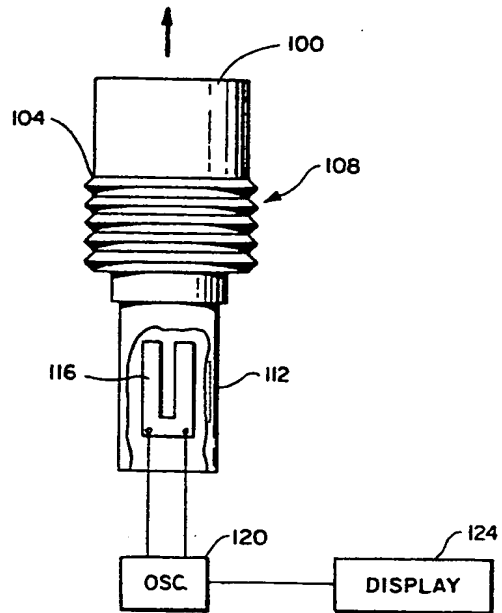


Fig. 5

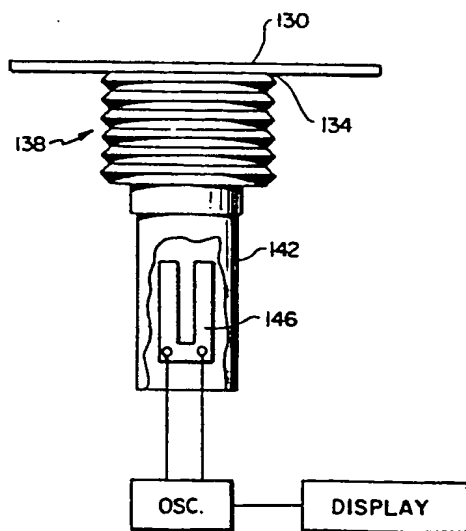


Fig. 6

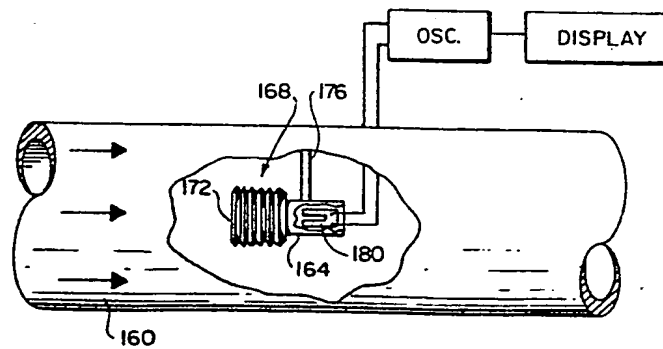
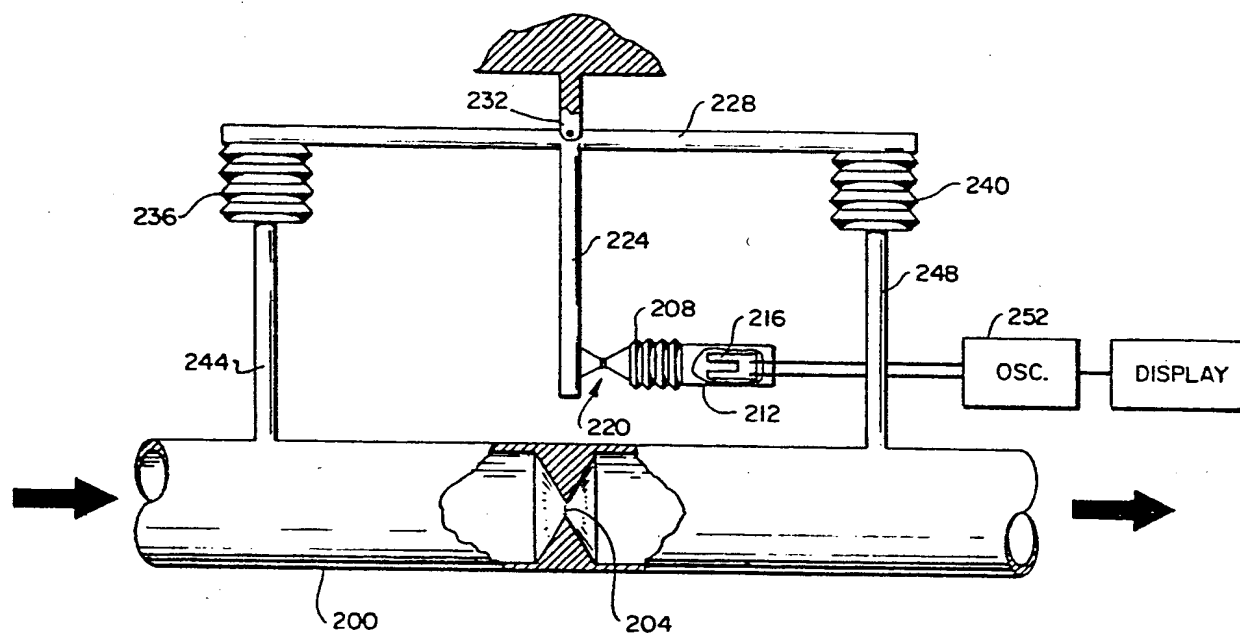


Fig. 7



**Fig. 8**



DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl. 3)
X	GB-A-2 079 940 (ITT INDUSTRIES) * Page 1, lines 1-23; claim 1; figures 1-5 *	1,2,30	G 01 N 9/00
A		6-8,12 ,14,15 ,25,28 ,29	
X	--- PATENTS ABSTRACTS OF JAPAN, vol. 5, nr. 146 (P-80) [818], 16th September 1981 & JP - A - 56 79 221 (HOKUSHIN DENKI SEISAKUSHO K.K.) (29-06-1981)	21,33	
X	--- US-A-3 426 593 (R.B. JACOBS) * Abstract; column 2, lines 37-62; figure 1 *	1	
A		22	TECHNICAL FIELDS SEARCHED (Int. Cl. 3)  G 01 N 9/00 G 01 N 11/00 G 01 L 9/00
A	--- PATENTS ABSTRACTS OF JAPAN, vol. 6, nr. 237 (P-157) [1115], 25th November 1982 & JP - A - 57 136 130 (SHARP K.K.) (23-08-1982)	1	
A	--- US-A-3 690 147 (H.W. KUENZLER) * Column 9, claim 1; figure 1 *	1,3	
	--- -/-		
The present search report has been drawn up for all claims			
Place of search THE HAGUE		Date of completion of the search 17-09-1984	Examiner ERRANI C.
<p>CATEGORY OF CITED DOCUMENTS</p> <p>X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document</p> <p>T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons &amp; : member of the same patent family, corresponding document</p>			



European Patent  
Office

# EUROPEAN SEARCH REPORT

0129753

Application number

EP 84 10 6547

Page 2

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl. 3)
D, A	US-A-4 126 049 (M.A. COTTER)  * Column 5, line 39 - column 6, line 33; figure 4 *	1, 6, 9, 21	
A	US-A-3 902 365 (B.A. KNAUTH)		
A	US-A-4 297 872 (K. IKEDA et al.)		
			TECHNICAL FIELDS SEARCHED (Int. Cl. 3)
The present search report has been drawn up for all claims			
Place of search THE HAGUE		Date of completion of the search 17-09-1984	Examiner ERRANI C.
<b>CATEGORY OF CITED DOCUMENTS</b>			
X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document		T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document	

EPO Form 1503, 03/82